FINAL REPORT

Title: Alaskan Tundra Fires During a Time of Rapid Climate Change

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Daniel H. Mann
University of Alaska Fairbanks

Benjamin V. Gaglioti
University of Alaska Fairbanks

Benjamin M. Jones
University of Alaska Fairbanks

Eric Miller
Bureau of Land Management

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List of Abbreviations / Acronyms

All are defined in the text

Keywords
Arctic tundra, fire ecology, climate change, greenhouse gasses, fire management

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Abstract

This project concerned tundra fires in Alaska and how climate-driven changes in fire regimes could impact Alaska's Arctic ecosystems. We used remote sensing, dendrochronology, field vegetation surveys, and paleoclimate reconstructions to accomplish three goals: 1) to identify the extent and timing of past tundra fires occurring in Arctic Alaska, 2) to document the effects of these fires on vegetation and permafrost, and 3) to determine how these effects might change in a warming, more variable climate. The main study area for this work was the Noatak River in Northwest Alaska, which has been one of the most fire-rich regions of the Arctic in recent decades, and which provides a useful analog for a more flammable tundra biome in the future. We found that, in addition to the already-identified constraints imposed by summer climate, Arctic tundra fires are limited regionally by ignition sources, and more locally by the type and amount of fuels available on the landscape. Over the last 50 years, 97% of the area burned was in two fuel types: tussock tundra and erect shrub tundra. Based on remote sensing data and on-the-ground observations, tundra vegetation typically recovers to pre-fire greenness values within three years after a fire. Tundra fires resulted in two phases of increased primary productivity as manifested by increased landscape greening relative to pre-fire normals. Phase One occurred in most burned areas 3–10 years after a fire, while Phase Two occurred 16–44 years after fires at sites where burning triggered near-surface permafrost thaw that led to the proliferation of erect shrubs. Satellite-derived vegetation productivity indices suggest that on a multi-decadal time scale (from 10 years before fires to 44 years afterwards), tundra fires act to enhance the cumulative primary productivity by ~7% and thus may act as a net greening agent. This fire-induced greening may act to partially offset a fire's climate-warming effects through greenhouse gas emissions and surface albedo changes following tundra fires, especially in cases where carbon-rich permafrost is not being thawed and ancient carbon is absent or evades combustion. A positive feedback in which fires lead to shrubification that leads to greening and more fires is currently operating in the Noatak valley, and this feedback could expand northward as air temperatures, fire frequencies, and permafrost degradation increase. However, this feedback will not occur at all locations. In the Noatak valley, the fire-shrub-greening feedback occurs infrequently in tussock tundra communities where low-severity fires and shallow active layers exclude shrub proliferation. Climate warming and enhanced fire occurrence will likely shift fire-poor landscapes into either the tussock tundra or erect-shrub-tundra ecological attractor states that now dominate the Noatak valley. In addition to these findings, we also developed new methodologies, including a 'flammability index' for tundra vegetation types, and a new method for analyzing the satellite-based Enhanced Vegetation Index that focuses on the effects of fire and removes any ongoing effects of warming observed in unburned areas.

Objectives

1) How does a warmer climate affect tundra fire regimes?
2) How do tundra fires affect the release of carbon stored in permafrost?
3) How resilient is tundra vegetation and the insulative peat cover to burning?
4) How does burning affect thermokarsting, the changes in the ground surface topography caused by the thaw of ice-rich permafrost?

These objectives directly addressed JFSP 2016 Task C1 *Implications of Changing Ecosystems* by exploring how ongoing climate change could alter the fire regime on Alaska's North Slope, and how these changes might affect carbon balance, vegetation cover, and geomorphic stability. Some of our work was also relevant to Task C5 *Post-Fire Landscape Management*, specifically how vegetation, fuels, and post-fire successional pathways may change as tundra ecosystems adjust to new fire regimes. The overarching goal of this project was to provide fire managers with a synthesis of existing knowledge and a balanced outlook about how changing ecosystems on Alaska's North Slope can best be managed in relation to wildland fires.

Because fire has been relatively rare on the North Slope and in other tundra regions with similar climatic regimes, we must look further south for a promising analogue that exhibits how the fire-poor zones of the Arctic could be transformed in the warming decades that lie ahead. The fire-rich Noatak watershed (Figures 1, 2) is an ideal analogue for the North Slope's future because both regions share similar vegetation types and both are underlain by continuous permafrost (Jorgenson et al., 2014; Raynolds et al., 2019). In addition, the fire regimes of the Noatak may also serve as a reasonable harbinger for the Arctic foothills region of the North Slope in the future because they share similar topography. Because fire is common in the Noatak, assessing how tundra ecosystems there have responded to recent burning offers a test for how sensitive permafrost is to burning and provides a case study for observing the fire regimes in the Arctic tundra. In addition, the Noatak watershed contains latitudinal treeline where the boreal forest transitions into Arctic tundra; these two vegetation types are currently in flux due to changes in temperatures and fire regimes. These project objectives were met by studying the effects of fires in the Noatak River Valley and on the North Slope of Alaska through on-the-ground vegetation and permafrost surveys, dendrochronology, and through remote sensing analyses.

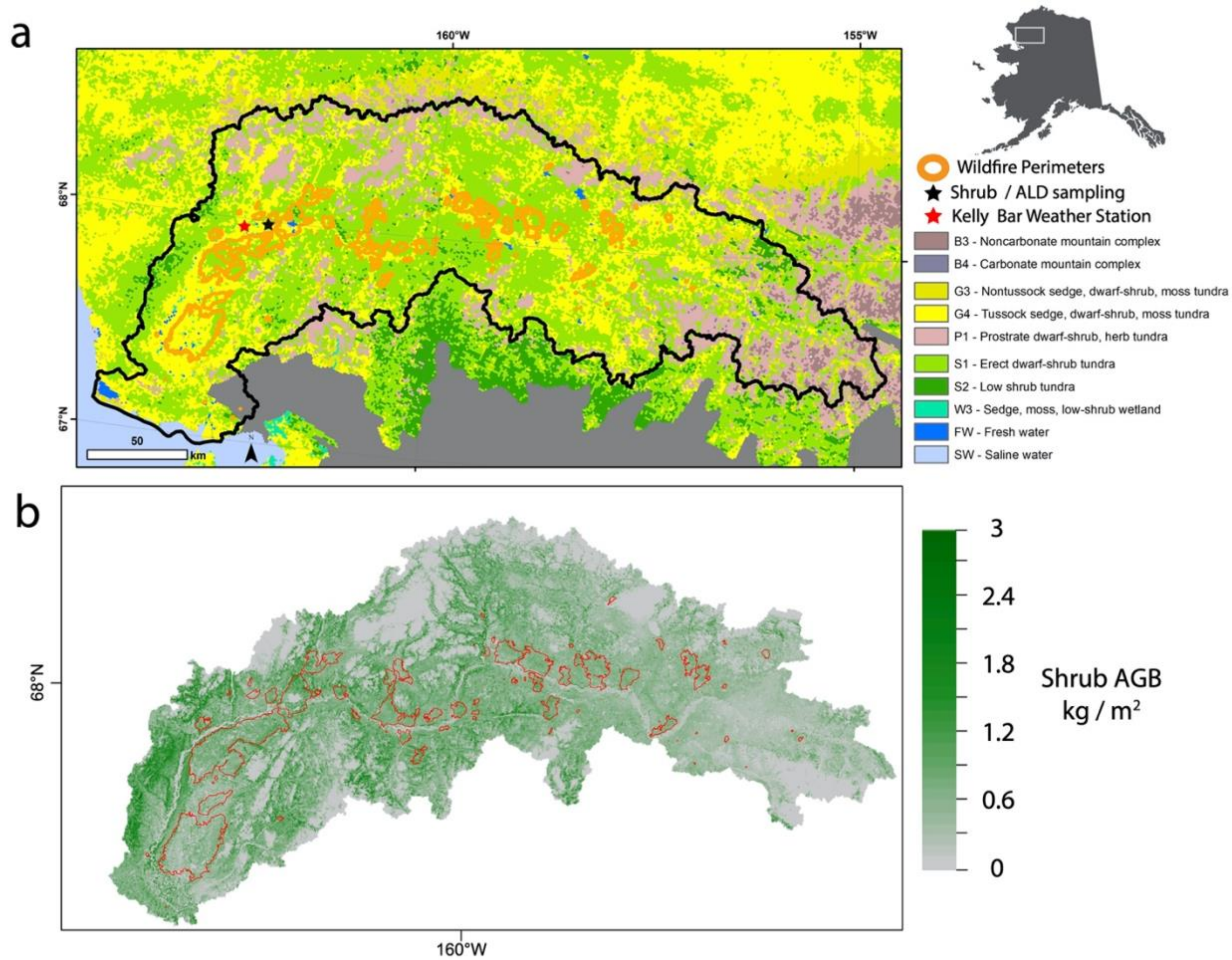

Figure 1. Map of Noatak watershed with shrub sampling site in Northwest Alaska overlain with tundra fire perimeters from AICC (2019). Base maps include a) vegetation type (Raynolds et al., 2019) and b) estimated shrub aboveground biomass (Berner et al., 2018).

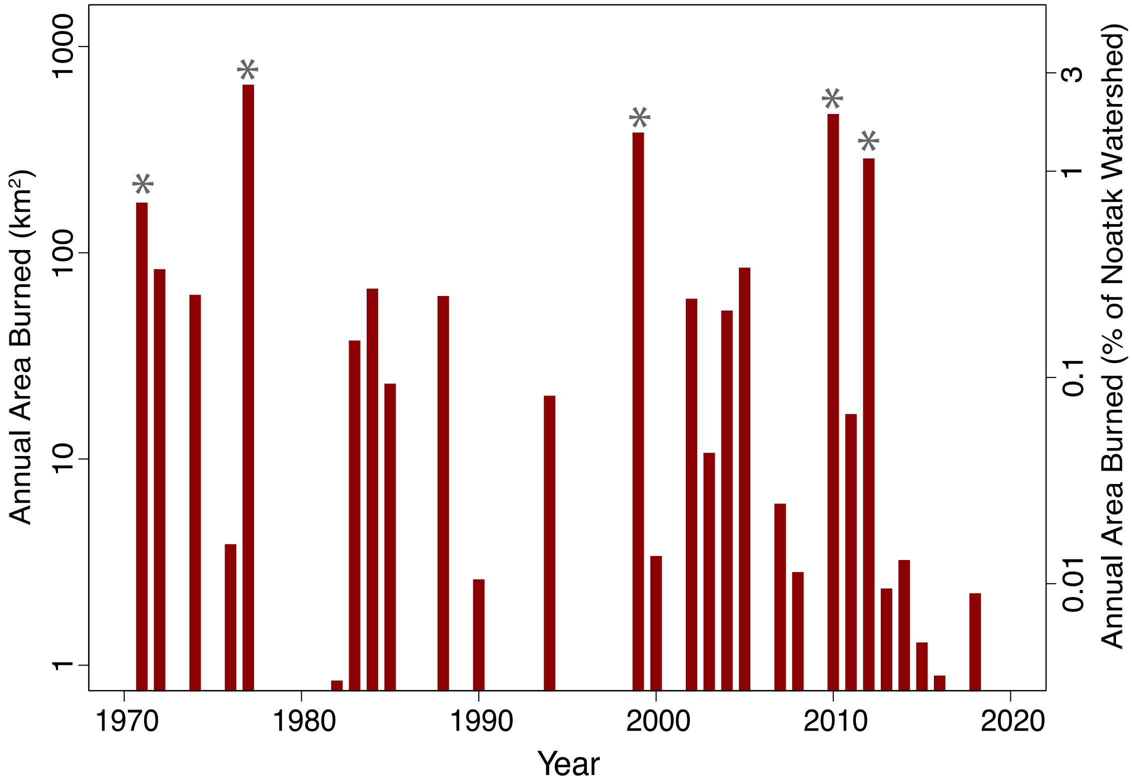

Figure 2. Time series of annual area burned (log scale; left y-axis), and percent of watershed burned in the Noatak drainage of Northwest Alaska (log scale; right y-axis) (AICC 2019). Gray stars denote the five years with the most annual area burned between 1971 and 2018. Figure from Gaglioti et al. (2021).

Background

1. Climatic implications for tundra fire regimes

Wildland fire is an important ecological disturbance within the tundra biome (Rocha et al., 2012), and increased burning will likely accelerate ecosystem responses to ongoing climate warming in certain parts of this biome (Landhausser & Wein, 1993; Racine et al., 2004; Hu et al., 2010). Rapid warming in the Arctic has already resulted in widespread permafrost thaw and the expansion of upright shrub communities in many regions (Tape et al., 2006; Smith et al., 2010; Martin et al., 2017). However, it may take decades to centuries for landscape responses to be fully realized because ecological responses to changes in climate can take longer in regions like the Arctic where plants are dormant much of the year (Chapin & Starfield, 1997). In addition, even the Arctic's relatively simple ecosystems have properties that buffer them from climate warming, with the result that ecological responses can be delayed or muted (Folke et al., 2004; Loranty et al., 2018). The primary negative feedback that currently buffers tundra in the Low Arctic (<70°N) from the effects of warming climate changes is the widespread presence of a surface organic soil horizon (peat), which insulates underlying permafrost from warming air temperatures (Figure 3a) (Yi et al., 2007; Baughman et al., 2015) and resists vegetation changes by virtue of its cold, water-saturated, and acidic growing medium (Tape et al., 2012). But the tundra's peat *can* burn during warm, dry summers (Jones et al., 2009; Mack et al., 2011), and shrub expansion and permafrost thaw *can* proceed rapidly after a fire combusts the peat cover (Jones et al., 2013; 2015). In short, when Arctic warming trends co-occur with tundra fires, post-fire ecosystem responses are more likely to equilibrate with 'the new normal' relative to a more tempered response in the absence of fire (Landhausser & Wein, 1993; Jones et al., 2013). A summary of how simulated ground temperatures change with varying peat layer thickness and our hypothesized changes of ecological responses to climate forcing with and without fire are shown in Figure 3.

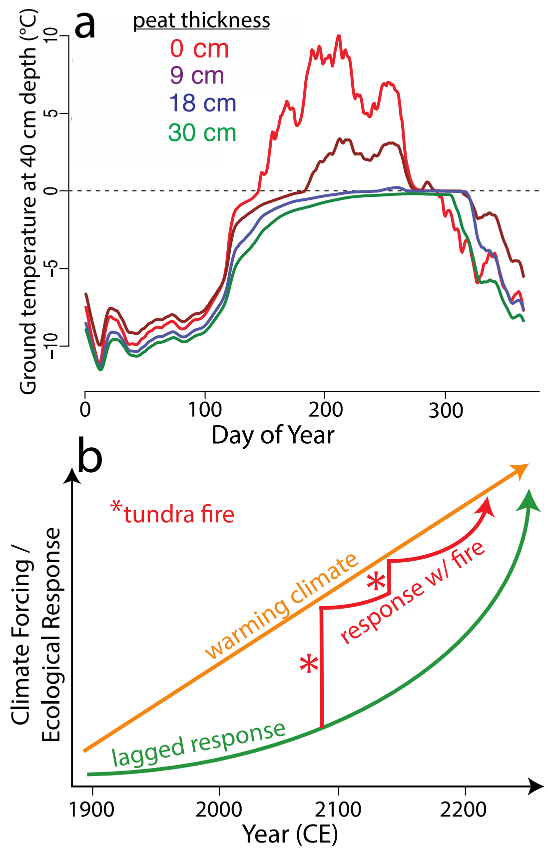

Figure 3 Surface soil organic layers (peat) currently make much of the low Arctic impervious to change because they buffer underlying permafrost from warming air temperatures and resist shrub expansion. a) Simulated ground temperature at 40 cm depth during a typical climatic year in Fairbanks, Alaska using the University of Alaska Geophysical Institute's Permafrost Laboratory' model (Marchenko et al., 2008). Each line represents a simulation with the same climate, but with different peat thickness. b) Hypothetical climate forcing and ecological responses in the Arctic tundra with and without tundra fires or other disturbances that overwhelm peat's negative feedbacks.

Arctic tundra fires are expected to become more frequent and severe over the coming century (French et al., 2015; Hu et al., 2015), and how this altered disturbance regime will affect peat's buffering capacity has global implications. Among the possible impacts of more frequent and severe fires and the associated removal of soil organic horizons is the release of soil carbon (C) to the atmosphere as greenhouse gases during the burning of vegetation and organic soils (Mack et al., 2011; Turetsky et al., 2011), and through subsequent enhanced soil respiration following fire-induced permafrost thaw (Rocha & Shaver, 2011; Gibson et al., 2018, 2019). Although not widely acknowledged in the literature today, at least a portion of this fire-derived carbon release is eventually re-stored in tundra ecosystems during post-fire vegetation and soil recovery (Bret-Harte et al., 2013). In this way, some proportion of the greenhouse gas emissions from fires should be considered as a temporary "loan" of carbon to the atmosphere, instead of the often-advertised irreversible "gift" of carbon to the atmosphere. When considering all aspects of this process, net greenhouse gas effects of tundra fires depend on both the emissions during fires, thaw-driven carbon release, *and* the processes of vegetation productivity and soil recovery following fire. In some cases, post-fire nutrient fertilization and permafrost thaw can enhance primary productivity (Racine et al., 2004; Rocha et al., 2012; Jones et al., 2013; Barrett et al., 2012; Heim et al., 2019), while in other cases tundra fires appear to have little effect on long-term primary productivity (Loranty et al., 2014). More observations that describe how vegetation productivity has responded since burning is crucial for determining if, when, and where post-fire vegetation trends compensate for C losses during and after fires.

2. Post-fire vegetation responses in Arctic tundra

To understand the potential for tundra fire regimes to change, we first need to understand the limits of the self-maintaining processes that control fire occurrence and distribution in the tundra biome. Consider for example the fire regime of tussock tundra vegetation dominated by *Eriophorum vaginatum* L. (cottongrass), whose growth architecture and life history are adapted to optimize their productivity on cold, organic-rich soils (Chapin et al., 1979). Individual cottongrass plants usually survive low-severity fires because their fresh tillering buds are protected inside a tussock consisting of many years of dead sedge leaves and tillers (Racine, 1981; Fetcher & Shaver, 1983; Vavrek et al., 1999). Despite being heavily charred during tundra fires, tussocks have the ability to immediately re-sprout and then exhibit enhanced rates of productivity and blooming (Wein & Bliss, 1973; Wein & Shilts, 1976). Racine et al. (1987) pointed out that tundra fires often release these fire-adapted cottongrass plants from interspecific competition because: 1) adjacent slowly-regenerating shrubs growing in inter-tussock areas have the potential to be completely combusted, freeing up sun and nutrients for the fire-enduring tussocks, and 2) post-fire permafrost thaw can lead to enhanced cryoturbation, which exposes mineral soil and is suitable for new tussock establishment accompanied by high rates of growth (Hall et al., 1978; Shilts, 1978). Tussock tundra is a relatively flammable vegetation type (Rocha et al., 2012), and low-severity burning releases tussocks from competition, which then allows them to persist, reproduce, and endure subsequent low-severity fires supported by their non-woody, fine fuels. Because of these properties, this vegetation-enabled fire regime is widespread where tussock tundra routinely dries out enough to carry fires in relatively warm tundra regions (Racine et al., 1985, 1987).

Another type of tundra fire regime occurs in erect shrub tundra. Where erect shrubs like birch and alder are widespread, fires can be more severe than those that burn tussock tundra because of the more abundant woody fuels are more likely to ignite and carry more severe fires (Higuera et al., 2008; Hu et al., 2015). Increased fire severity is then more likely to cause active-layer deepening, which triggers thermokarst activity, which in turn promotes the establishment of more shrubs and further increases in primary productivity, including higher rates of woody fuel buildup (Lantz et al., 2010, 2013; Jones et al., 2013; 2015). We call this fire regime feedback the 'fire-shrub-greening positive feedback' because the shrub-rich vegetation that proliferates after intense fires support more severe burning that leads to further shrubification, and so on. A variation of this fire regime appears to have maintained a highly flammable, shrub-dominated tundra vegetation in northwest Alaska during the Late Glacial period (14-10 thousand years ago) (Higuera et al., 2008, 2009). Areas covered in tussock tundra may be replaced by this alternative, erect-shrub tundra fire regime if enough woody-fuel build-up accompanies shrub expansion that has been triggered by either climate warming and / or enhanced post-fire permafrost thaw (Lantz et al., 2010, 2013; Myers-Smith et al., 2011).

Several fire-related issues relevant to the future of the tundra biome remain unresolved. These include the extent to which the shrub-fire-greening feedback is currently operating in flammable tundra regions. We do not know whether ongoing warming will activate this shrub-fire-greening feedback loop in otherwise fire-scarce tundra and usher in a shrubbier vegetation structure that is more prone to intense fires.

Another unresolved question is whether recent warming and enhanced burn severity are capable of overcoming the self-maintaining features of tussock tundra fire regimes and negative peat feedbacks. Answering this question is important because overcoming these feedbacks would allow these relatively climate-impervious systems to shift into the more climate-sensitive fire-shrub-greening feedback. These questions can be assessed by surveying the productivity and types of tundra vegetation that typically burn in tundra fires, and by quantifying how different types of tundra vegetation responded after burning.

3. Tundra fires in Alaska

Currently, tundra fires are most common in warmer, more lightning-rich regions covered in shrub and tussock tundra vegetation (Rocha et al., 2012; French et al., 2015; Hu et al., 2015; Masrur et al., 2018). Rates of burning dramatically increase where mean summer temperatures exceed 11°C, total precipitation falls below 150 mm (Hu et al., 2015), and when summer sea-ice cover is relatively low (Hu et al., 2010). One region where these climatic thresholds are predicted to be crossed in the near future is the North Slope of Alaska, which is the size of Great Britain, and is broadly representative of the Low-Arctic tundra. Tundra fires are thought to have been rare on the North Slope prior to AD 1900; however, large pre-historic tundra fires have been discovered there (Jones et al. 2013), and they now appear to be occurring more frequently than in the recent past (Chipman et al., 2015; French et al., 2015; Hu et al., 2015).

Our overall research question is: What are the patterns and processes of ecosystem responses to tundra fires in Northwest Alaska? Our specific research questions include:
1) Where on the landscape have tundra fires overcome the negative feedbacks of peat and resulted in post-fire greening / shrubification?
2) Is the fire-shrub-greening positive feedback currently operating in the Noatak watershed?

As described above, the implications of these results are relevant to the trajectory of tundra ecosystems within the warmer, more flammable Arctic of the near future.

Materials and Methods

Because most fires in the remote Noatak region have not been directly monitored in real time, we employ methods that retrospectively describe the ecological impacts of fires. These methods include shrub dendrochronology, active-layer depth monitoring, and remote sensing. The first two approaches involve the application of traditional methods and therefore are not described in detail in this report. Briefly, we used dendrochronology and active-layer-depth monitoring to estimate the rate of shrub growth, shrub recruitment, and permafrost thaw depth at three adjacent sites possessing different burn histories (*no burn, burned once, and burned twice since 1972*). We refer the reader to Gaglioti et al., (2021) for a full description of these methods. For the remote-sensing methods in this project, we made two new methodological contributions, and so we will describe these in detail here.

We use the Landsat satellite record of remotely sensed vegetation productivity to describe post-fire vegetation responses from 1989 to 2016. For this analysis, we use a chronosequence of different aged burns. The 2-band Enhanced Vegetation Index (hereafter, EVI2; Jiang et al. 2008) was used as a proxy for annual photosynthetic activity in all available years at randomly sampled points differing in burn history and other biophysical characteristics. The EVI2 represents a snapshot of the degree of red absorption and therefore of landscape greenness after taking into account atmospheric absorption and surface reflectiveness. We chose EVI2 over the Normalized Differential Vegetation Index (NDVI) because EVI2 is more sensitive to the post-fire responses of tundra vegetation and is more accurate in quantifying changes in tundra vegetation canopy structure, through near infrared reflectance (Rocha & Shaver, 2009), which is a common vegetation response to wildfires in the Noatak watershed (Racine et al., 2006). EVI2 is linearly related to both tundra net ecosystem exchange (Rocha & Shaver, 2011) and leaf area index (Rocha & Shaver, 2009), as well as correlated with gross primary productivity across ecosystem types (Rahman et al., 2005).

Our first methodological contribution involved isolating fire effects on the EVI2 index and therefore on the vegetation. To do this, we compared each annual, burned EVI2 value to the entire unburned EVI2 distribution for that same year (hereafter, $EVI2_b$). This $EVI2_b$ index thereby captures the greenness of burned vegetation *relative* to unburned vegetation during the same growing season (Figure 4b). Without this relative perspective, post-fire vegetation changes due to the effects of burning cannot be separated from ongoing, non-fire-related greening or browning trends experienced by vegetation throughout this region of the Arctic (Figure 4a). This is particularly important in tundra regions, where significant warming-driven greening trends have occurred in the last several decades (Myers-Smith et al., 2020; Berner et al., 2020). By using the $EVI2_b$ index, we can remove these climate-driven greening trends and isolate the effects of tundra wildfire on vegetation productivity.

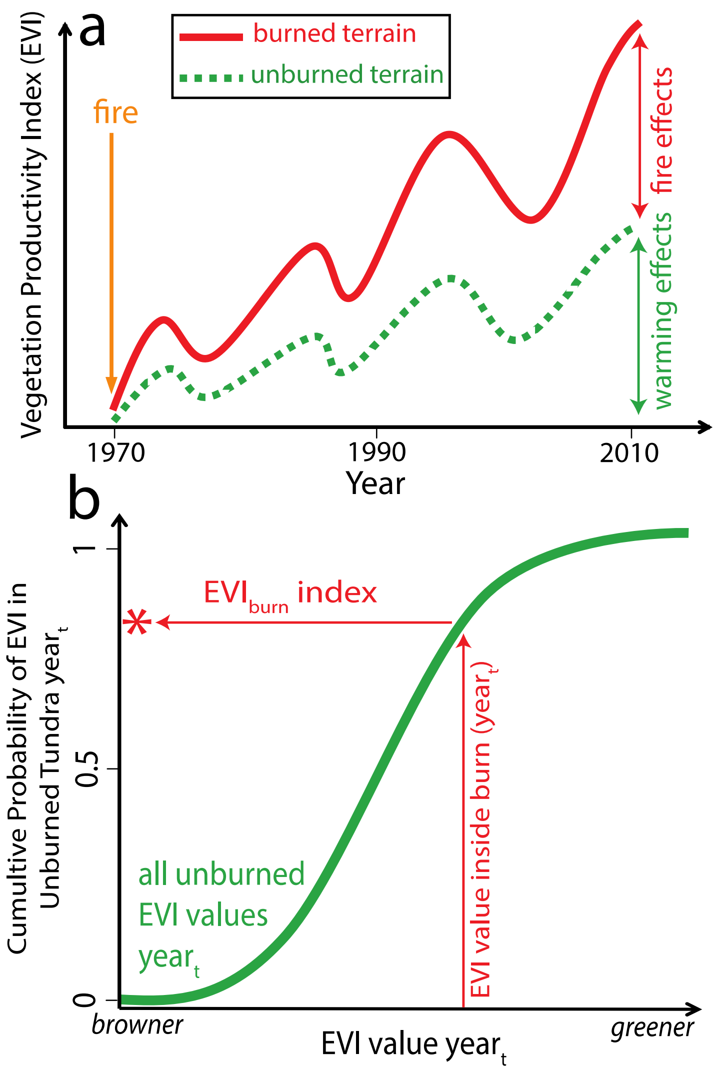

Figure 4. a) Remotely sensed vegetation indices are affected by both climate and fires in the Arctic tundra. b) In order to isolate the effects of fires, we calculated the EVI2$_{burn}$ index by placing each annual EVI2 value in burned areas into the context of all unburned observations for the same calendar year.

The second methodological contribution we made in the course of this project was a flammability index (FI) for seven different CAVM vegetation types (Raynolds et al., 2019). These layers include: fellfield barrens, erect shrub tundra, low shrub tundra, non-tussock sedge tundra, prostrate shrub tundra, wet sedge tundra, and tussock sedge tundra.

Eq 1. $$FI = V_b / V_t$$

In the *FI* index, V_b is the vegetation type's percent cover within historically burned areas in the Noatak River watershed, and V_t is the percent of the total watershed occupied by that same vegetation type. A FI index >1 indicates that a vegetation type is over-represented in areas that burned and is therefore relatively fire prone.

Results and Discussion

I. Fuel Controls over Tundra Fires in Arctic Alaska

1) ***The growth rates of tundra shrubs, which can serve as highly flammable fuels for tundra fires, will continue to increase as June temperatures rise.***

This finding was reported in Andreu-Hayles, et al. (2020) (*see project products*), and is based on a dendrochronological network of tundra shrubs across the North Slope of Alaska. Annual ring-widths in willow and alder shrubs were positively correlated to daily temperatures during a relatively short seasonal window between May 31st and July 1st since 1982 (Figures 5, 6). Two lines of evidence indicate that shrub expansion has recently occurred at these locations: 1) Most of the sampled shrubs germintated after 1980, and 2) A significant positive trend of increasing growth rates has occurred since 1960. Continued warming is likely to enhance shrub growth rates and lead to an increase in woody fuels in this region of Arctic tundra.

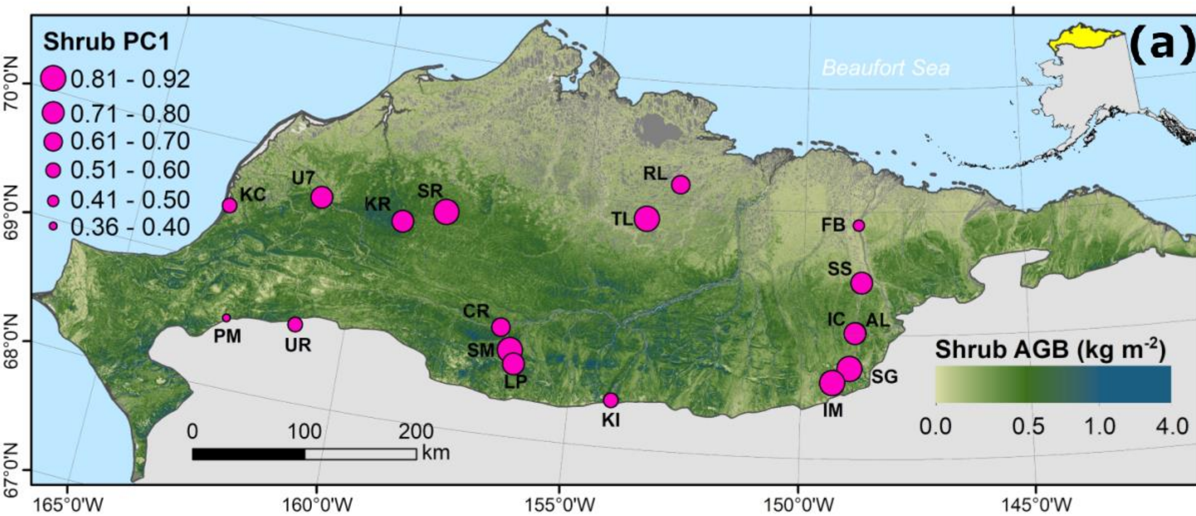

Figure 5 Study area and shrub sites from Andreu-Hayles (2020) Location of the 18 shrub ring-width chronologies. The size of the circle is proportional to the loading of each site with the first principal component (PC1) of a Principal Components Analysis (PCA) of the entire shrub ring-width network from 1991 to 2006. Background map of shrub aboveground biomass (AGB) from Berner et al. (2018).

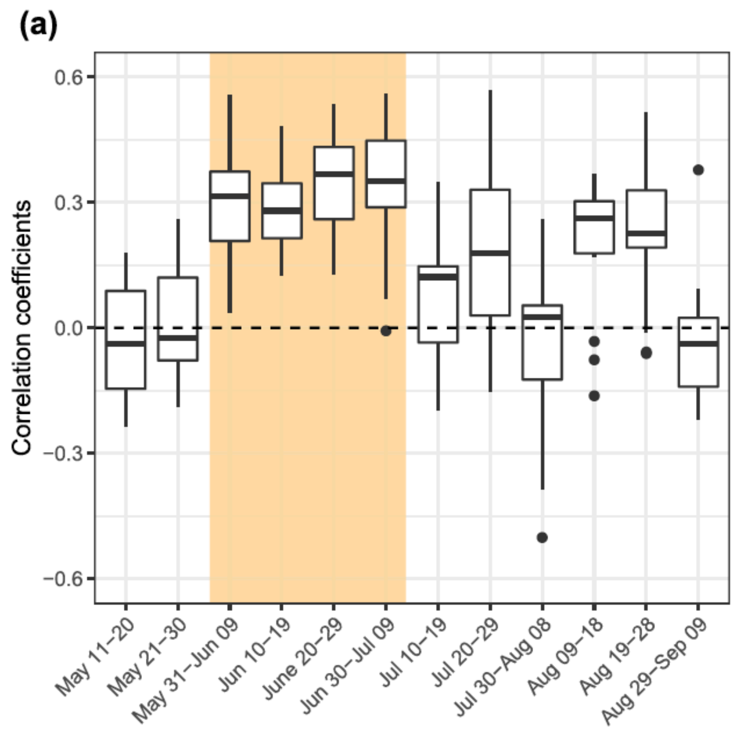

Figure 6 Correlation coefficients between annual ring widths in Arctic shrubs and maximum daily temperatures for different ten-day intervals during summer. Orange highlighted area shows the period when Arctic shrub growth is most sensitive to air temperatures.

2) Tundra fires in the flammable Noatak Valley are more likely to occur in areas that have more productive vegetation types. Within these areas, vegetation types with higher above-ground productivity are the most likely to burn.

This finding was presented in Gaglioti et al., (2021). It is based on the Enhanced Vegetation Index, a remotely sensed indicator of tundra plant productivity during the years before fires. We found that these areas were significantly greener (more productive) prior to burning relative to areas outside fires. This is also true when we look at the Enhanced Vegetation Index of burned areas prior to fires that are restricted to tussock and shrub tundra.

3) Tundra fires in the Noatak Valley mainly occur in tussock tundra and upright shrub tundra communities.

We found that 97% of all burning occurred in these two vegetation types. This finding was based on the flammability index of vegetation types in the Noatak Valley (Figure 7).

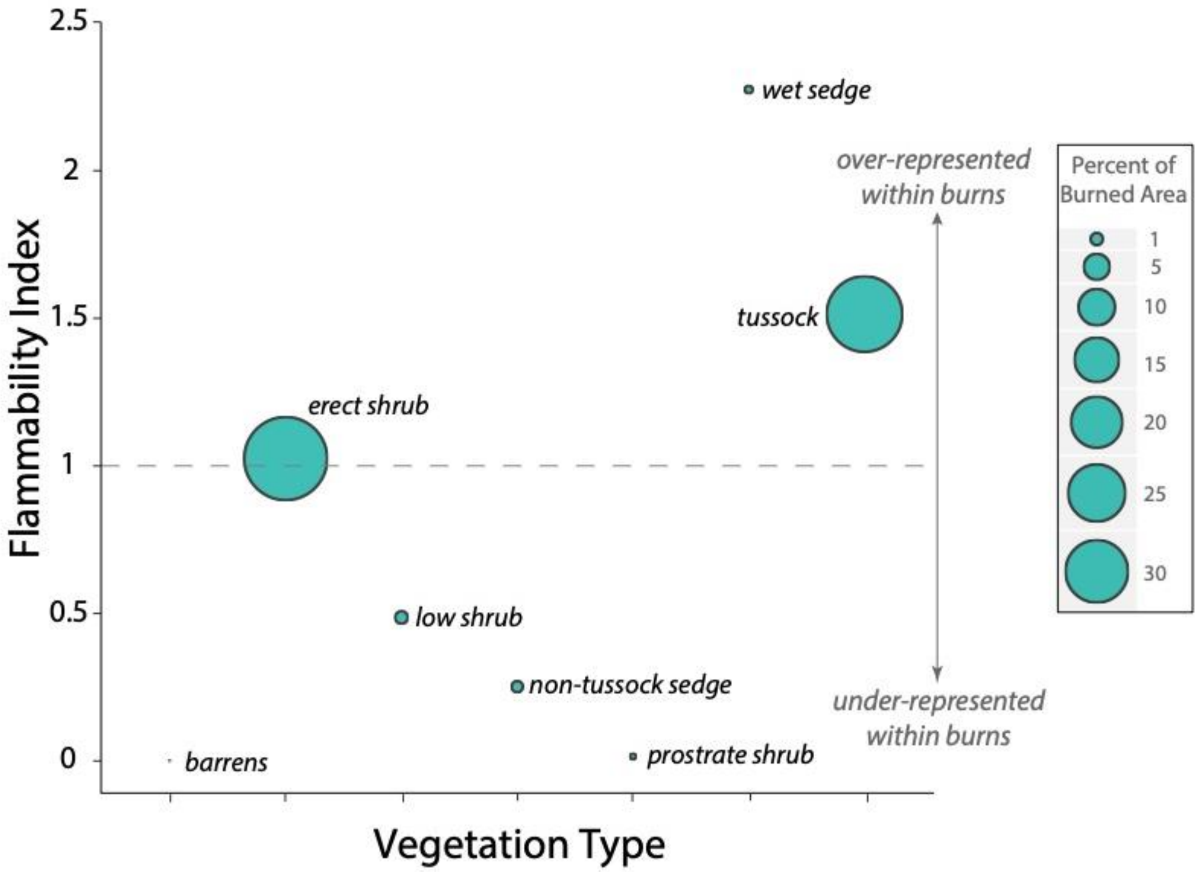

Figure 7 Flammability index and percent of total burned area (AICC, 2019) for the seven different vegetation types in the Noatak watershed (Raynolds et al., 2019). Figure from Gaglioti et al. (2021).

Based on these results, we conclude that tundra wildfires in the Arctic are fuel limited, which implies that their frequency will increase in response to a warming-driven increase in primary productivity. Overall, these data suggest that the amount and type of fuels influence the distribution and severity of tundra fires, at least in this relatively flammable area of the Arctic. Furthermore, most tundra burning occurs in just two vegetation types (tussock and erect shrub tundra). The vegetation-mediated fire regimes that exist in the Noatak imply that a warming-driven increase in tundra fire occurrence will be moderated by the velocity and pathways of warming-driven vegetation change (as in Higuera et al., 2009). In other words, only when plant communities change, will their fire regimes also change.

II. Climate controls on Tundra Fires in the Noatak

1) The most frequently burning tundra regions in Arctic Alaska are warmer and have greater lightning strikes per area.

This finding was reported in a talk given to the Alaska Fire Science Consortium group in March 2020 by co-PI Ben Gaglioti (Figures 8, 9). This analysis was conducted by comparing the precipitation, temperature, and lightning regimes of a relatively flammable tundra region (the Noatak River Watershed) with a relatively fire-scarce region (the North Slope of Alaska).

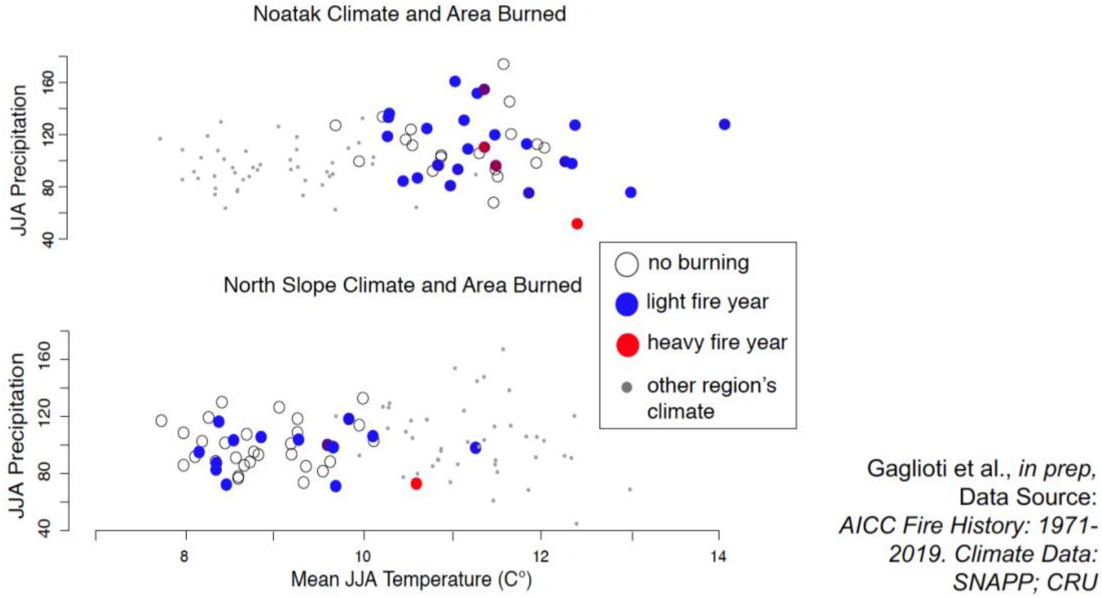

Figure 8 Summer climate of the Noatak and North Slope showing heavy fire years. Summers in the more flammable Noatak region are ~2°C warmer than on the North Slope.

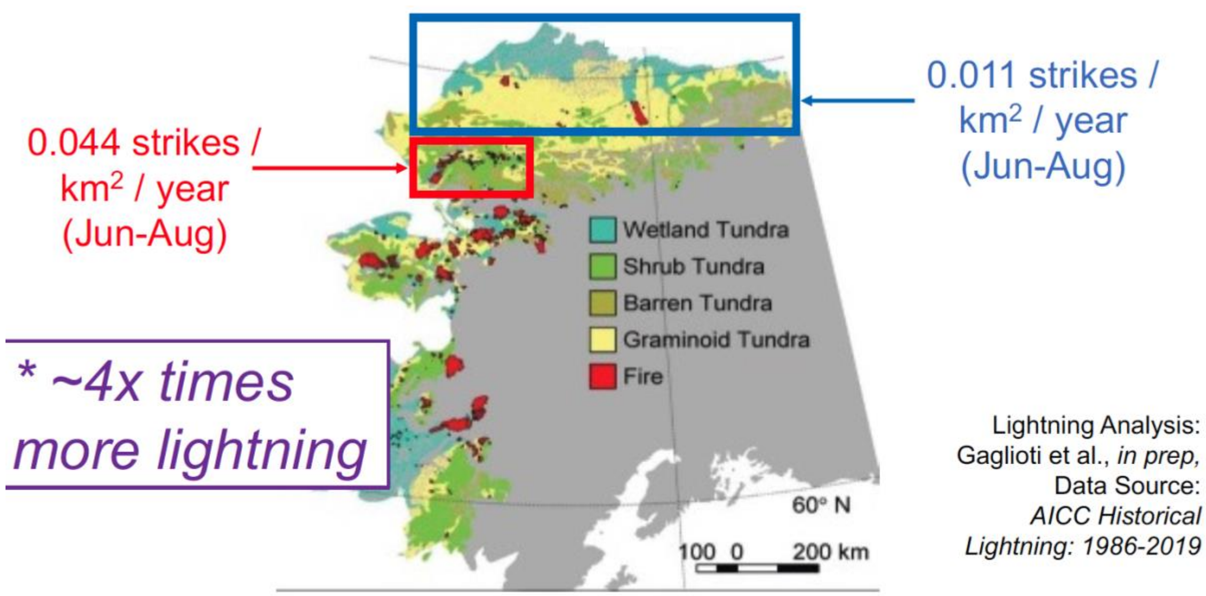

Figure: Hu et al., 2015 *Frontiers in Ecology and Evolution*

Figure 9 Based on Alaska Interagency lightning monitoring data, the Noatak valley has ~4x more lightning strikes between June and August during the 1986-2019 period. This enhanced ignition source likely contributes to the Noatak having 14x more burn area per unit area relative to the North Slope. Base map showing tundra vegetation types and fire polygons is from Hu et al., (2015).

III. Effects of Tundra Fires in Arctic Alaska

1) Post-fire vegetation recovery takes 3-5 years depending on burn severity.

Field observations and shrub dendrochronology in the Noatak region indicate that vegetation began regenerating a year or two after burning in 1984, or, in some cases, plants survived fires with only minimal damage. Surface greenness in the sixty fires we analyzed recovered to pre-fire values within 3-5 years of burning. With the exception of the most severely burned areas, tundra vegetation typically returned to pre-fire greenness within just three years after most of the area burned (Figure 10).

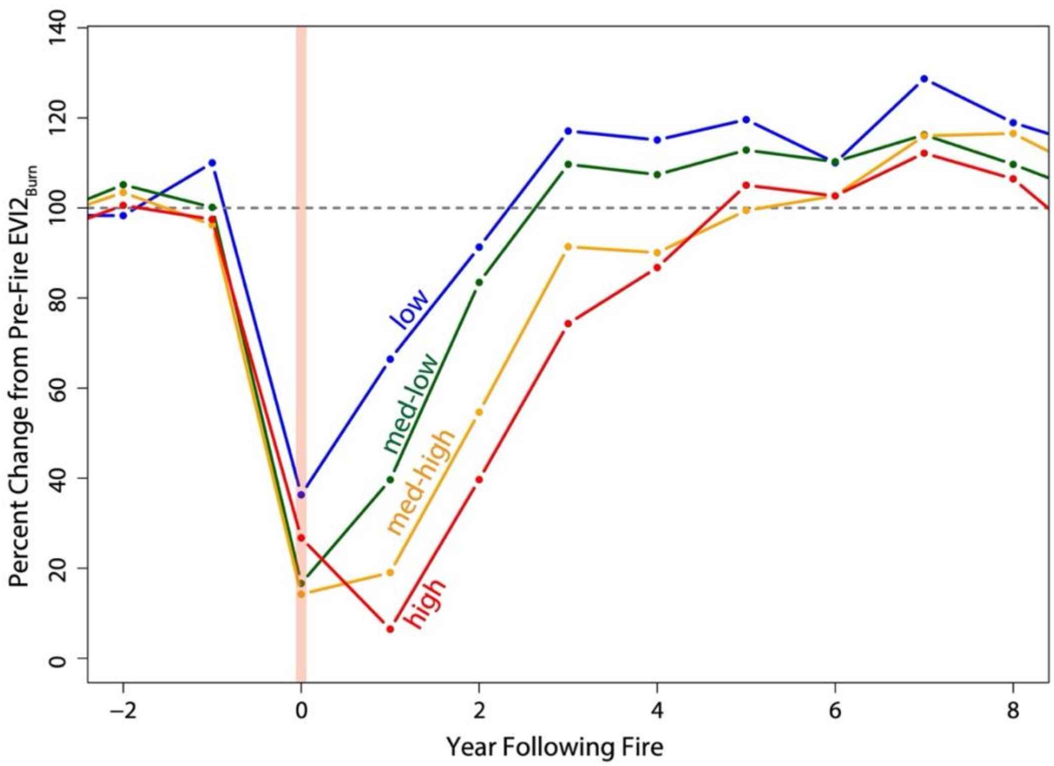

Figure 10 Percent changes of post-fire $EVI2_b$ relative to the five years before fires for locations that varied by burn severity. Burn severity classification is from Loboda et al. (2018).

The three-year post-fire vegetation recovery that we see here has been observed in other tundra regions of Alaska (Rocha et al., 2012). This is a rapid recovery compared with the boreal forest, where more severe, ground-carried crown fires and multiple seres of plant succession involve slow-growing conifers. The shorter post-fire recovery time observed in the Noatak is partly attributed to tundra fires being lower in severity than forest fires because of significantly lower fuel loads and because of the thermal state of the soil when tundra fires occur. Regarding the latter, most wildland fires in in the Noatak valley occur before July 5th (AICC, 2019), when active layers are still thin and both plant rhizomes and seed banks are sheltered from burning in wet or frozen soils (Hinzman et al., 1991), which enables them to re-sprout soon after fire occurrence.

As observed in other remote-sensing and field-based studies, the rapid recovery of land-surface greenness following tundra fires suggests that the initial stage of post-fire vegetation succession involves re-sprouting of plants that survived a fire (Wein & Bliss, 1973; Racine et al., 1987; Landhausser & Wein, 1993; Bret-Harte et al., 2013). We observed that tundra fires often scar the cambium of shrubs that survive a fire, which allows faster replenishment of woody fuels in the post-fire tundra. It remains to be seen how common fire-scarring is in tundra shrubs, or what life history traits tundra shrubs have evolved for fire avoidance, but shrub scarring has implications for the speed of post-fire vegetation recovery and for dating prehistoric fires using wood morphology (i.e., Gaglioti et al., 2016). Other life-history traits of the dominant plants that serve as fuel for tundra fires include the protected rhizomes of fire survivors like cottongrass and hydrophillous and mesic sedges, which, shortly after a fire, are able to re-sprout from unburned tiller buds (Wein & Bliss, 1973; Fetcher & Shaver, 1983; Racine et al., 1987; Vavrek et al., 1999).

2) The rate of post-fire shrub expansion is dependent on the degree of permafrost thaw occurring after a fire.

Gaglioti et al. (2021) reached this conclusion based on: 1) the enhanced annual growth rates of shrubs in burned areas where significant permafrost thaw, occurred, and 2) the significant increase in surface greenness in burned areas where near-surface permafrost was vulnerable to thaw and where shrub seed sources were present (Figure 11). Alder shrubs growing in areas burned twice since 1972 grew about 3x faster than those growing in nearby unburned areas. The twice-burned areas had significantly greater late-summer depth to thaw (active-layer depths) indicating warmer soils. In contrast, the shrubs growing in areas that only burned once had only moderately deeper active layer depths and similar shrub growth rates in unburned areas. We also found that shrubs growing inside burn perimeters had significantly greater values than just outside. This finding indicates that shrub proliferation is triggered by recent burning.

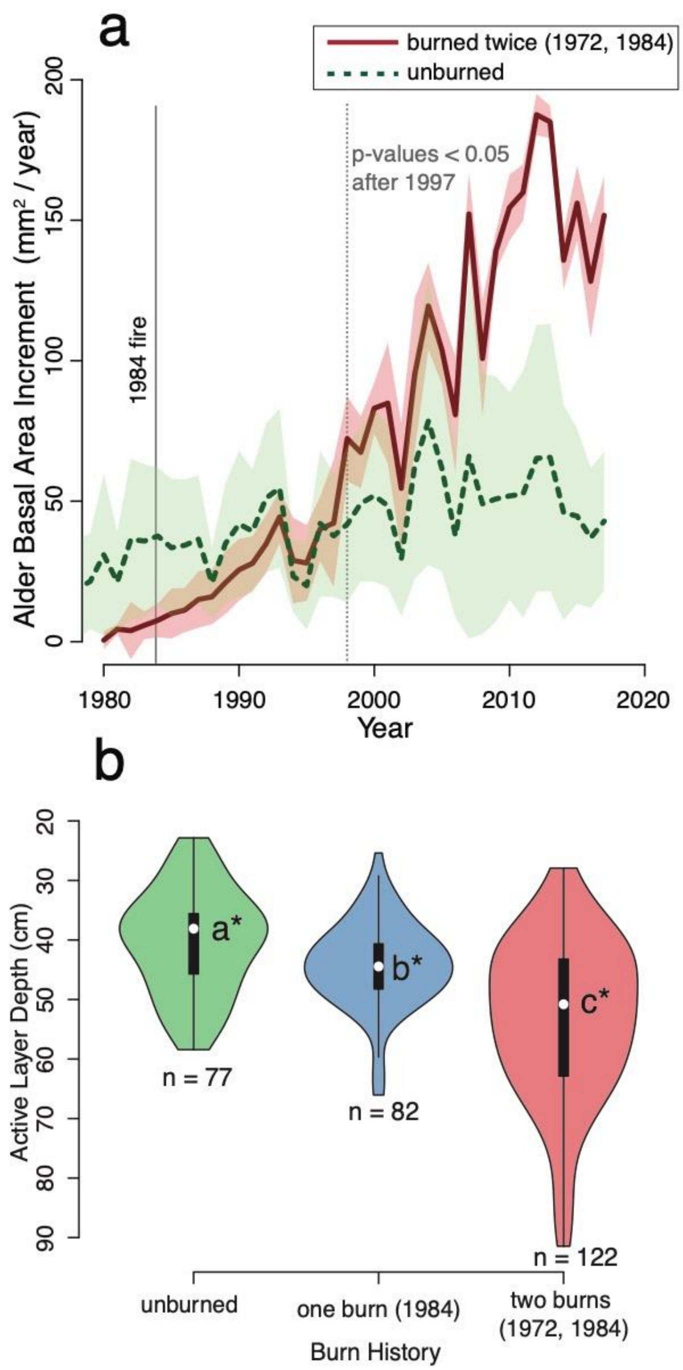

Figure 11 a) Mean (lines) and standard deviation range (shading) of basal area increments of alders growing in areas with different burn histories. Years to the right of dotted lines indicate times when alders growing in an area that burned twice (1972 and 1984) have significantly greater growth rates than alders growing in an area that went unburned since at least 1970, b) Active layer depths in areas with different burn histories showing the median (dots), interquartile range (vertical black bars), 1.5x interquartile range (vertical black lines) and the kernel density estimation to show the probability distribution of the data (outer margin). Different letters denote significantly different means (p<0.05).

3) Significantly greener tundra occurs for several decades after fires in the Noatak valley. This post-fire greening occurs in two episodes: 3-7 years following fire, and again 15 to at least 44 years following fires (Figure 12).

Part two of this post-fire greening roughly coincides with how long it takes shrubs in recently burned areas to exceed the growth rates of shrubs growing in nearby unburned areas (Figure 11). Therefore, we suspect that this second post-fire greening episode represents shrub expansion.

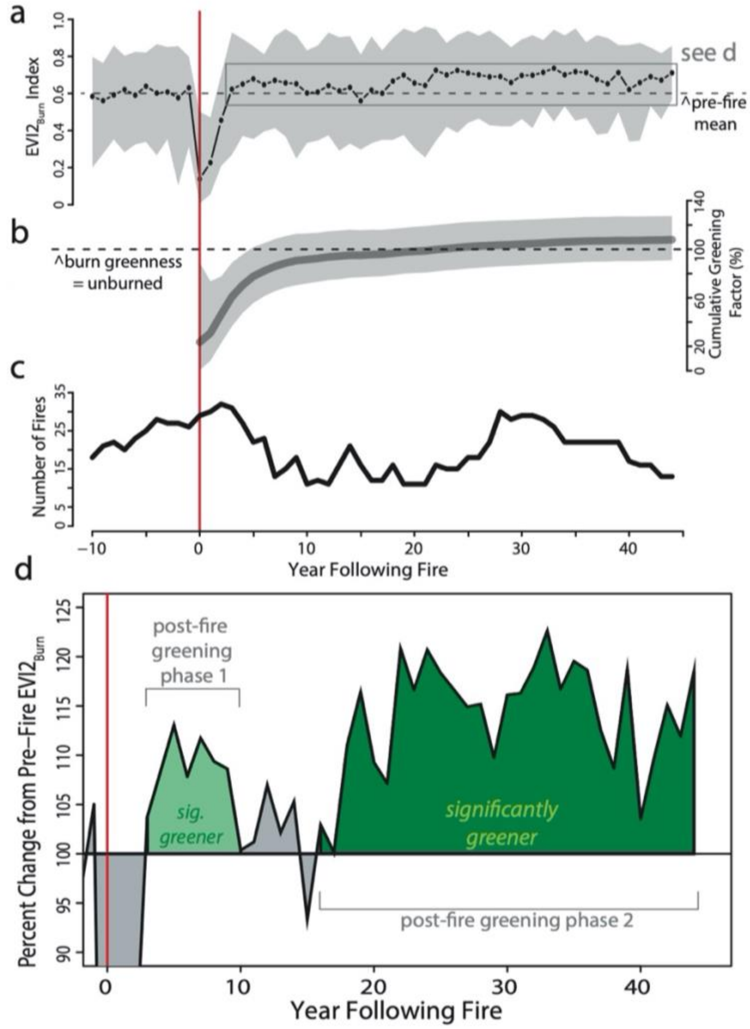

Figure 12. a) Mean and 95% confidence intervals of $EVI2_b$ indices for all fires. Dashed line is the 10-year pre-fire mean (0.60). b) Cumulative post-fire greening relative to pre-burn $EVI2_b$ values. Percentages >100 indicates post-fire greening has compensated for $EVI2_b$ reduction during the three years following burning. c) Number of fires with $EVI2_b$ values contributing to this record over time. Vertical red line indicates the year of fire event. d) Closeup of a) showing the percentage change of burn EVI2 relative to pre-fire values (6-1 year before fires). Green shading indicates when post-fire $EVI2_b$ values are significantly greater than those 5-1 years before fires (p<0.05).

The distribution and timing of the first post-fire greening phase provides clues about the processes that cause post-fire vegetation to become greener three and ten years after a burn. This first greening phase is evident in the $EVI2_b$ values when all data points are combined (Figure 12d), for areas that burn with low severity, as well as areas that are underlain by continuous permafrost (Figure 9a), have >50% segregation ice (Figure 13c), areas underlain steeper and coarser lithologies, and covered in erect shrub tundra (Figure 13b). Earlier work indicates that plant and soil combustion during boreal and tundra fires tends to enhance nutrient availability in the years following fire, including enhanced available phosphorous and nitrogen, nutrients that limit primary productivity in the low-Arctic tundra biome (Wein & Bliss, 1973; Bret-Harte et al., 2013; Jiang et al., 2015). The temporary nature of the first greening phase may be due to the rapid plant re-growth rates and higher nutrient availability during the post-fire recovery period, which is then rapidly exhausted (Jiang et al., 2015; Larouche et al., 2015). Our results also suggest that phase one of post-fire greening is nutrient-fueled because it occurs most often in nutrient-limited sites that support peat-producing plants, contain wet soils, and are underlain by continuous permafrost. Overall, phase one of post-fire greening is widespread, and, because post-fire nutrient increases are common following fires (Knicker, 2007), short-term post-fire greening will likely persist even as fire regimes change in the future.

Phase two of post-fire greening consists of a shift to an average ~14% greener land cover by ca. 16 years after fires (Figure 12d). We hypothesize this represents post-fire shrub expansion that is facilitated by permafrost thaw. Evidence supporting this hypothesis includes: (1) It takes ca. 15 years for this greening phase to begin after fires, which roughly coincides with the time it took for annual growth rates of alder shrubs in twice-burned areas to surpass alder growth rates in adjacent un-burned areas (ca. 13 years; Figures 12a). This agreement between shrub ontogeny and remotely sensed vegetation data indicates that the onset of greening phase two is consistent with direct, albeit limited, measurements of post-fire shrub expansion. (2) Phase two greening is confined to areas underlain by continuous permafrost, in areas where permafrost has an estimated >50% segregated ice content, and where sediment types are coarser and terrain is steeper. These are areas with abundant, near-surface ground ice that is likely to partially thaw after fire, and in areas of well-drained soils that experience a shift to greater soil drainage after thaw. When thawed, this type of terrain experiences ground subsidence, and exposure of bare-soil patches, which are then available for plant colonization. Due to these landscape processes, these are also the portions of the landscape where warming-driven shrub expansion has been most pronounced over the last 80 years in the Noatak Valley and on the North Slope of Alaska (Tape et al., 2012). The spatial distribution of greening phase two supports the idea that significant permafrost thaw is often a pre-requisite for fire-induced vegetation greening (Liljedahl et al., 2007; Yi et al., 2009; Jones et al., 2013, 2015). Our results also suggest that post-fire permafrost-thaw-induced greening occurs through post-fire shrub expansion, which is captured in both our remote sensing record and dendrochronology results. (4) Finally, post-fire greening phase two is rather limited in tussock tundra where upright shrub seed sources are limited (Figure 13). Locally abundant shrubs before a fire provides local seed sources and immediate post-fire re-sprouting from unburned tissue. Overall, fires appear to enhance vegetation productivity for at least 45 years following fires, particularly in areas where thaw-induced shrub expansion occurs.

The timing and distribution of this two-phased greening pattern indicates that the negative feedbacks related to peat cover can be surpassed in situations where near-surface permafrost is vulnerable to thaw and soils are relatively well-drained. Tussock tundra is one fire-prone vegetation type where phase two of post-fire greening is limited. The thick peat that helps maintain cold, wet soils that are favorable for tussocks also create conditions for a fire regime with low severity surface fires that do not degrade the underlying permafrost. Part of the fire-insensitive features of tussock tundra involve the architecture of tussocks, which protect their vulnerable buds in a wet mass of old leaves and tillers. Another reason that tussock tundra seems to be inured to post-fire greening is that inter-tussock areas often harbor moss communities, which retain moisture and provide a significant insulative layer that protects the underlying permafrost. Our results suggest that the most paludified areas with wet sedge and tussock vegetation and/or with fine-grained sediments, and/or where permafrost thaw has already occurred may not be as vulnerable to long-term permafrost and vegetation change until further warming and/or more severe burning occurs. Our findings suggest that the self-maintaining fire regime operating in tussock tundra rarely leads to significant long-term (decadal scale) changes in productivity, and the vast majority of the non-shrubland tundra that burns ends up in the fire-adapted tussock formation state. Due to the effects tundra fire regimes have on promoting this tussock vegetation type, we hypothesize that this is one ecological attractor state that will become more widespread as tundra fires become more common in the fire-poor tundra found today at higher latitudes (e.g., the North Slope of Alaska). Additional warming and greater burn severity of unknown magnitudes appear to be needed in order to shift tussock vegetation out of the negative feedback loops that now maintain them in their current state (Figures 14, 15).

4) Post-fire greening over several decades eventually compensated for the reduced productivity during the three years immediately following tundra fires in the Noatak valley.

From an $EVI2_b$ perspective, tundra fires resulted in enhanced levels of primary productivity (+7%) over 44 years post-fire (Figure 12b). Because EVI2 is a surrogate for net ecosystem exchange in tundra regions (Rocha & Shaver, 2011), tundra fires in the Noatak *may* serve as agents of carbon sequestration because post-fire greening results in more productive vegetation than would have occurred if these areas went unburned. The cumulative $EVI2_b$ productivity index changed from negative to positive 22 years after fires, which suggests that tundra fires are greening agents only when fires occur at >22-year intervals.

There is a growing concern that wildfire-derived carbon emissions will exacerbate global warming (Mack et al., 2011; Turetsky et al., 2015; Walker et al., 2019). This has led to proposals to suppressing Alaska's wildfires in order to curtail greenhouse gas emissions (Grissom et al., 2000). Our results and those of post-fire soil carbon assessments in Siberian tundra (Loranty et al., 2014) imply that these efforts must take into account post-fire vegetation recovery and greening that may partially compensate for the losses of carbon during and after burning.

5) Post-fire greening depends on landscape position.

Greening is limited in areas that do not have near-surface permafrost, have limited shrub seed sources and thick organic deposits associated with tussock tundra, and that have relatively low ground-ice content. Figure 13.

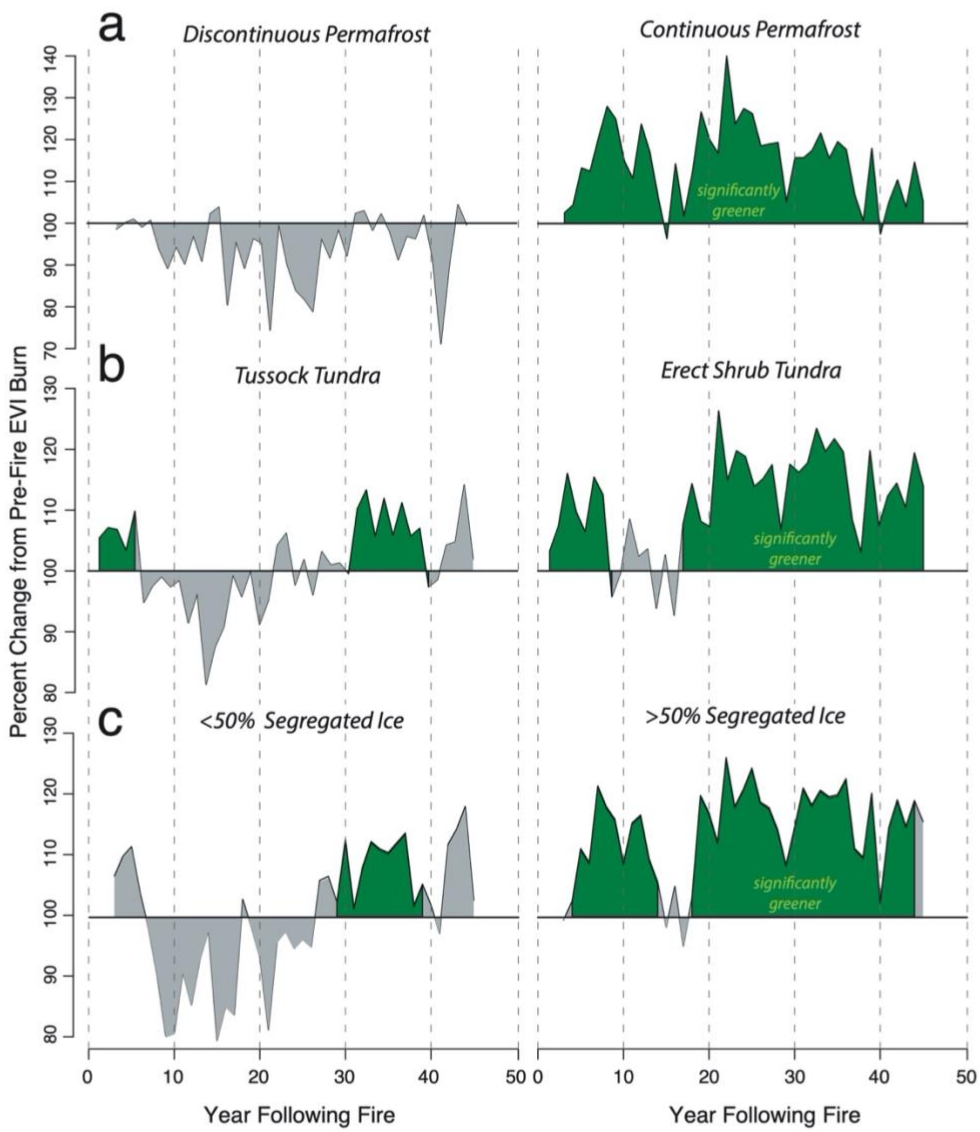

Figure 13. Percentage change of $EVI2_b$ relative to pre-fire values (5-1 years before fires) for burned terrain that varies in a) permafrost type (Jorgenson et al., 2014) b) vegetation type (Raynolds et al., 2019), and c) percent segregated ice (Jorgenson et al., 2014). Green polygons indicate when post-fire $EVI2_b$ values are significantly greater than those 5-1 years before fires ($p<0.05$).

6) The fire-shrub-greening feedback in the Noatak Region

Our results show that more productive, shrubbier areas burn more severely in the Noatak watershed and that tundra fires often result in increased productivity and more shrub biomass. These results suggest that the negative feedbacks related to peat in many areas in the Noatak Valley have limits and are susceptible to being pushed by fire and a warming climate across a critical threshold that results in a shift to shrublands, or at least to an enhanced shrub cover in existing shrublands (Figure 14, 15). The more severe burning supported by these shrublands then prevents a return to a paludified steady state (as observed in Jones et al., 2013). Because the addition of fire on the landscape tends to cause a shift towards this fire-prone, erect shrub tundra community type, this is another ecological attractor state that we should expect to become more widespread during the fire-rich future of Arctic tundra. Because the North Slope of Alaska and much of the circumpolar Low Arctic (<70°N) has similar vegetation and permafrost characteristics as the Noatak valley, these regions may be susceptible to similar regime shifts and to the positive fire-shrub-greening feedback that we observe here. Based on these results, these shifts and feedbacks will be especially prevalent in areas where permafrost thaw leads to enhanced soil drainage and shrub expansion following fires (Racine et al., 2006; Lantz et al., 2010, 2013; Jones et al., 2013; Frost et al., 2020).

If the fire-shrub-greening feedback has been operating in the Noatak for some time, why isn't the entire watershed covered by erect-shrub tundra that burns severely? We suggest four ways landscapes either avoid this ecological attractor state or end up escaping from this feedback loop (Figure 15). First, even under a warming climate, fire is still a stochastic disturbance, and some locations invariably escape burning for long periods of time regardless of fuel buildup. In these situations, undisturbed vegetation and soil buildup may proceed far enough to revert back to a paludified landscape where shrub expansion is curtailed and even reversed. Second, there are areas where the self-maintaining features of the tussock tundra fire regime prevent a shift into the erect-shrub fire regime. In these situations, tussocks endure frequent, low-severity fires that kill their shrub competitors, and these sites remain in the aforementioned tussock ecological attractor state. Third, due to fire-independent conditions related to surficial geology, hydrology, ground-ice content, and soil, shrubs may be incapable of flourishing in some areas until more intense warming and/or burn severity occurs. Fourth, there *is* an exit pathway out of the fire-shrub-greening feedback that can occur in areas where an invasion of spruce trees ushers in a boreal forest fire regime. These possible exemptions to and exits from the fire-shrub-greening feedback loop should be considered when forecasting tundra fire regimes in a warming climate. The self-maintaining qualities of the shrub-greening and tussock-enduring maintenance fire regimes make up the two attractor states for flammable tundra in the Noatak, where they contribute to ~97% of burned area. Where and when tundra ecosystems enter and exit these attractor states will help determine the vegetation mosaic of the tundra biome in a warming Arctic.

Conclusions

We found the tundra plant communities in the Noatak watershed are highly stable despite repeated fire disturbances. Vegetation re-sprouting and partial vegetation damage contribute to vegetation indices recovering to pre-fire values within about three years post-fire. Satellite-derived vegetation-productivity indices indicate that on a multi-decadal time scale (from ten years before fires to 44 years afterward), tundra fires act to increase primary productivity by ~7% and thus act as a net greening agent. This fire-induced greening may partially offset a fire's contribution to climate warming through greenhouse gas emissions and surface albedo changes following tundra fires, especially in cases where carbon-rich permafrost is *not* being thawed and where ancient carbon is either absent or evades combustion.

Post-fire greening occurred in two stages. Phase one occurs between 3 and 10 years after a fire in most terrain types, which we hypothesize is caused by enhanced nutrient availability. The second phase of post-fire greening is more likely to occur in places where fire triggered near surface permafrost thaw that led to shrub expansion. The timing of this second phase of greening matches how long it takes shrub growth in thawed, burned areas to exceed growth in unburned and less-thawed areas.

A fire-shrub-greening positive feedback appears to be operating in much of the Noatak valley where the presence of more shrubs facilitate more severe burning, which thaws permafrost and begets further shrub proliferation, which is accompanied by warmer soils. This positive fire-shrub-greening feedback is down-regulated by conditions that prevent post-fire shrub expansion due to pre-existing conditions related to soil, permafrost, and surficial geology, which have too-high a shrub-exclusion threshold for current climate warming and fire regimes to close this feedback loop. Theoretically, a warming-driven increase in the rate and severity of tundra burning *could* cause a regime shift from tussock tundra to tall shrub tundra, but this tussock-to-shrub regime shift appears to have been uncommon in the recent past, and both tussock tundra and erect shrub tundra fire regimes - which dominate the burned area in the Noatak - are operating somewhat independently through their separate, self-maintaining processes. Elsewhere, the fire-shrub-greening feedback is diverted to alternative states, as in areas that remain fire-free long enough to become paludified, or where boreal tree species establish after fires. Both the tussock and shrub fire-regime feedbacks have the potential to force fire-poor tundra into their attractor states as climate change makes tundra fires more likely at high, northern latitudes.

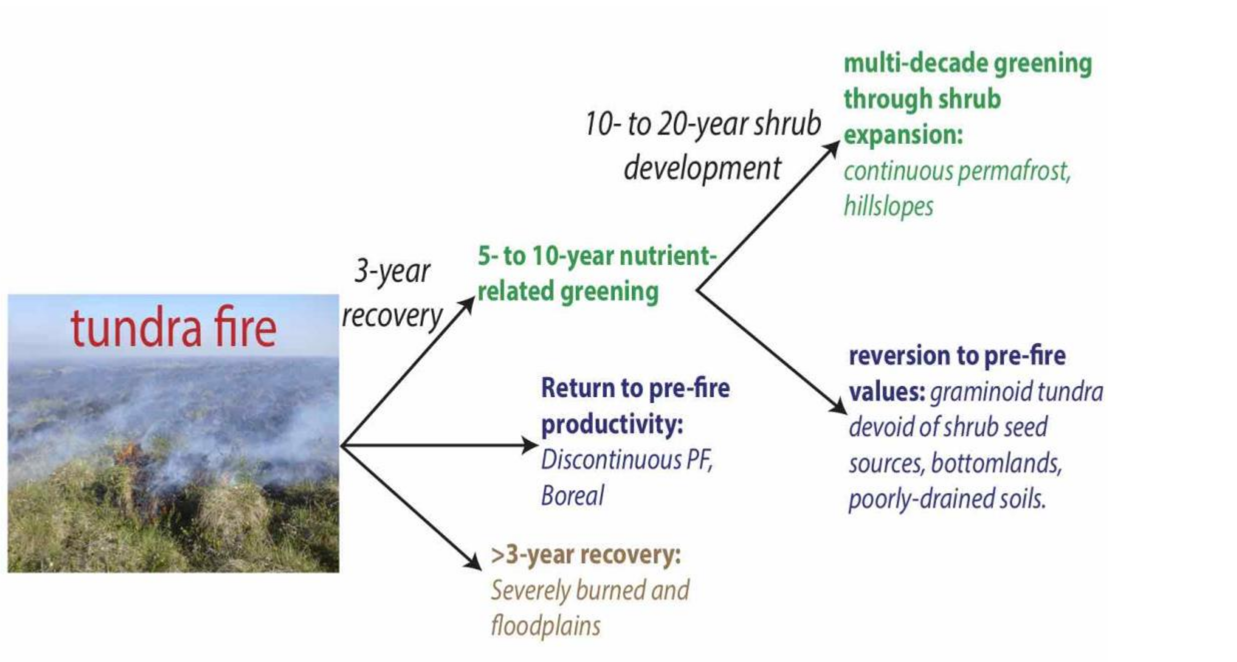

Figure 14. Timing and pathways of post-fire tundra vegetation for different landscape situations in the Noatak watershed.

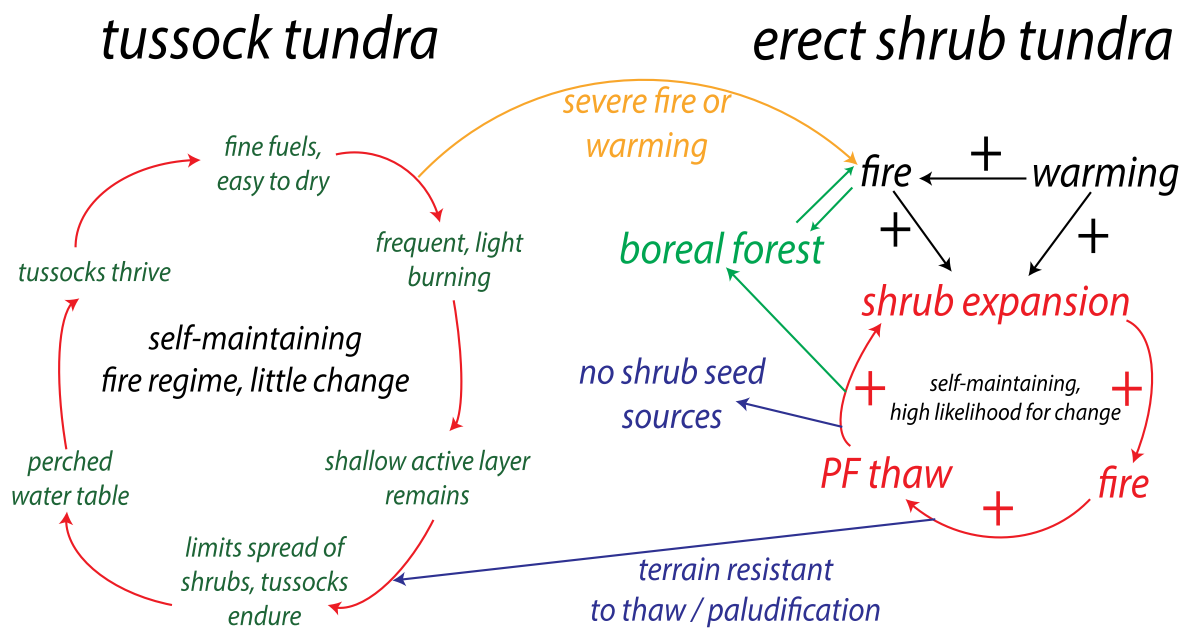

Figure 15. Two tundra fires regimes are operating simultaneously in the Noatak watershed. Tussock tundra is a self-maintaining feedback loop that leads to little vegetation change except in the most severely burned areas. In erect shrub tundra, a positive feedback likely helps maintain a tundra fire regime where warming- or fire-driven shrub expansion leads to more severe burning and permafrost thaw, which leads to enhanced greening and more fire. But there are several pathways out of this self-maintaining feedback that involve: 1) paludification when fire-free periods become unusually long, which can lead back to tussock tundra, 2) areas where fire does not cause thaw, or where near-surface thaw has exhausted the vulnerable permafrost, and 3) areas where post-fire vegetation pathways lack shrubs or transition to boreal forest due to seed source availability. The self-maintaining properties of these feedbacks likely contributes to these two vegetation types being responsible for the 97% of the burned vegetation in the Noatak Valley

Implications for management

1) Tundra fires are of global concern because of their potential for releasing some portion of the immense amount of carbon stored in high-latitude soils. If this is in fact the case, it may be necessary to actively suppress tundra fires. This would be spectacularly expensive due to the vastness of the region involved and its remoteness. Our results from the Noatak valley indicate that tundra fires may often have the opposite effect on the net carbon budget. Namely, enhanced plant growth after burning causes a gain in carbon storage that would not have occurred otherwise.

2) Our Noatak valley study area is an excellent analog for Alaska's North Slope in coming decades as climate warms, permafrost thaws, and biota shift their ranges northward. It follows that fires will almost certainly increase on the North Slope in response to warming climate, northward penetration of convection storms, and shrubification. These fires will increasing threaten human infrastructure and will contribute to sweeping changes in the biota and geomorphology of this vast region.

3) Recovery of vegetation and permafrost processes are rapid (several decades) following medium to low severity fires in the Noatak valley compared to the century-long recovery times observed in the boreal forest. This implies that subsistence uses also recover to pre-fire levels relatively rapidly in tundra areas. The exception to this will be in areas underlain by ice-rich, deep deposits of *yedoma*, as in parts of the North Slope.

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Appendix A. Contact Information for Key Personnel

Principal Investigator

Daniel H. Mann:
dhmann@alaska.edu
Institute of Arctic Biology, University of Alaska Fairbanks

Co-Principal Investigators

Benjamin V. Gaglioti:
bengaglioti@gmail.com
Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska Fairbanks

Benjamin M. Jones:
bmjones@alaska.edu
Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska Fairbanks

Eric Miller:
eamiller@blm.gov
Bureau of Land Management and the Alaska Fire Service

Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products:

1. Articles in Peer-Review Journals

Gaglioti, B.V., Berner, L.T., Jones, B.M., Orndahl, K.M., Williams, A.P., Andreu-Hayles, L., D'Arrigo, R.D., Goetz, S.J. and Mann, D.H., 2021. Tussocks enduring or shrubs greening: Alternate responses to changing fire regimes in the Noatak River Valley, Alaska. *Journal of Geophysical Research: Biogeosciences*, *126*(4), p.e2020JG006009.

Andreu-Hayles, L., Gaglioti, B.V., Berner, L.T., Levesque, M., Anchukaitis, K.J., Goetz, S.J. and D'Arrigo, R., 2020. A narrow window of summer temperatures associated with shrub growth in Arctic Alaska. *Environmental Research Letters*, *15*(10), p.105012.

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Nitze, I., Grosse, G., Jones, B.M., Romanovsky, V.E. and Boike, J., 2018. Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic. *Nature communications*, *9*(1), pp.1-11.

Gaglioti, B.V., Mann, D.H., Williams, A.P., Wiles, G.C., Stoffel, M., Oelkers, R., Jones, B.M. and Andreu-Hayles, L., 2019. Traumatic resin ducts in Alaska mountain hemlock trees provide a new proxy for winter storminess. *Journal of Geophysical Research: Biogeosciences*, *124*(7), pp.1923-1938.

2. Conference or symposium abstracts

Gaglioti, B.V., Berner, L.T., Jones, B.M., Orndahl, K.M., Williams, A.P., Andreu-Hayles, L., D'Arrigo, R.D., Goetz, S.J. and Mann, D.H. Tussocks enduring or shrubs greening: Alternate responses to changing fire regimes in the Noatak River Valley, Alaska. *American Geophysical Union Fall Meeting, December 2020.*

3. Presentations/webinars/other outreach/science delivery materials.

Gaglioti, B.V., Berner, L.T., Jones, B.M., Orndahl, K.M., Williams, A.P., Andreu-Hayles, L., D'Arrigo, R.D., Goetz, S.J. and Mann, D.H. Tussocks enduring or shrubs greening: Alternate responses to changing fire regimes in the Noatak River Valley, Alaska. Oral Presentation Given at *American Geophysical Union Fall Meeting, December 2020.*

Gaglioti, B.V. The Environmental Legacies of Tundra Fires in the Noatak River Valley of Alaska. Seminar given to the Alaska Fire Science Consortium, April 2020.

Appendix C: Metadata

Data consists of shrub ring-width measurements (0.001 mm resolution) from alder shrubs growing in areas with different burn histories. These data can be found at the International Tree-Ring Data Bank. Ring Widths Once-Burned Site (https://www.ncdc.noaa.gov/paleo-search/study/32562) Ring Widths Twice-Burned Site (https://www.ncdc.noaa.gov/paleo-search/study/32563); Ring Widths Unburned Site (https://www.ncdc.noaa.gov/paleo-search/study/32564).

Another dataset includes remote sensing data, which includes the Enhanced Vegetation Indices for thousands of locations in the Noatak Valley of Alaska as well as active layer depth measurements of areas with different burn histories. These data can be found at the NSF Arctic Data Center (https://arcticdata.io/catalog/view/doi%3A10.18739%2FA2DV1CP69).